

Feasibility study of a laser ion source for primary ion injection into the Relativistic Heavy Ion Collider electron beam ion source^{a)}

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Charge state 1+ ions are required as a primary ion source for Relativistic Heavy Ion Collider-electron beam ion source (RHIC-EBIS) at BNL and laser ion source (LIS) is a candidate as one of the external ion source since low energy and low charge state ions can be generated by lower power density laser irradiation onto solid target surface. Plasma properties of ^{27}Al , ^{56}Fe , and ^{181}Ta using the second harmonics of Nd:yttrium aluminum garnet laser (0.73 J/5.5 ns and 532 nm wavelength) for low charge state ion generation was measured. Charge state distribution of Ta was optimized for 1+ with estimated laser power density of $9.1 \times 10^8 \text{ W/cm}^2$ on the target. It has been shown that the LIS can produce sufficient ion charge with the appropriate pulse structure to satisfy injection requirements of the RHIC EBIS. © 2008 American Institute of Physics.

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INTRODUCTION

The Relativistic Heavy Ion Collider electron beam ion source (RHIC-EBIS) is a new preinjector for the RHIC and NASA Space Radiation Laboratory being built at Brookhaven National Laboratory¹ to provide high beam current, highly charged heavy ion beam. The RHIC-EBIS will provide ion beam pulses of many species with a 5 Hz repetition rate and will be able to change species pulse to pulse basis. Charge state 1+ ions will be provided by an external ion source where they will be further ionized to the desired charge state.

A laser ion source (LIS) which produces ions by a pulsed high power laser irradiation onto the solid state target is a candidate of the external ion source since it has many advantages suitable for an external ion source. Only ions are transported and injected to the EBIS trap region so there is no contamination. Almost all the solid state target can be used as a target. Ion injection into the electron beam ion trap which is equivalent to EBIS, in principle, was already demonstrated at the Heidelberg electron beam ion trap,² and also comparison between LIS and other sources.

CONCEPTUAL DESIGN

Figure 1 shows a conceptual design of the RHIC-EBIS using LIS. It consists of three sections which are the LIS

section, the transport line, and the RHIC-EBIS. The LIS part includes the laser, target chamber, and plasma expansion chamber.

The target and plasma expansion chambers are in the vacuum of about 10^{-4} Pa and are isolated from the rest of the beam line to allow the extraction of ions with energies up to 20 qkV. These regions will operate at a potential several hundred volts higher than those of the drift tubes forming EBIS ion trap. Several different target materials are located inside the target chamber to be able to change ion species on a pulse by pulse basis. The optimal plasma drift length varies according to the species since the speed of expansion is different for different target species atomic masses. No bias

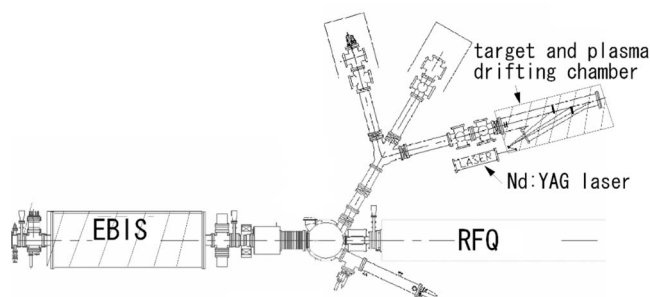


FIG. 1. Conceptual design of the LIS for RHIC-EBIS. The LIS target chamber and the plasma expansion chamber will operate at a potential several hundred volts higher than that of the drift tubes forming the EBIS ion trap (approximately 20 kV). High voltage areas are shown as the hatched area in this figure.

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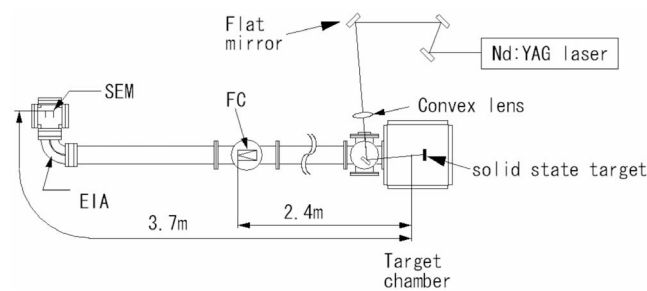


FIG. 2. (Color online) Experimental setup to analyze plasma properties.

voltage is applied to the target. The potential of the target chamber and expansion chamber can be varied according to ion energy at the extraction section to minimize the chromatic aberrations of the ion beam. The ion energy can be calculated based on time of flight information from a laser irradiation because the time period to generate plasma (few nanoseconds) is much shorter than plasma drifting time (more than tens of microseconds). The required voltage $U(t)$ to minimize energy spread of ions is

$$U(t) = U_0 - \frac{ms^2}{2e} \times t^{-2}, \tag{1}$$

where U_0 is an intended energy to be achieved after extraction, m is an ion mass, s is a drift length, and e is an elementary charge. The extracted ion beam is transported and injected to the EBIS. Ions are decelerated inside EBIS drift structure to several hundreds of eV in order to increase its linear charge density and, therefore, the number of ions which can be captured during a round trip transit of the EBIS trap region. After the trap region is filled with ions, the trap potential is closed.

EXPERIMENTAL SETUP

Figure 2 shows a schematic view of our setup to measure the charge state distribution of the laser ablation plasma. The second harmonics of Nd:yttrium aluminum garnet laser (0.73 J/5.5 ns and 532 nm wavelength) was used. All vacuum chambers including a target and measurement line was grounded. A laser light was focused by a convex lens ($f=800$ mm) located outside of the vacuum window, then, after passing the window, it was transported by a mirror toward the target with an incident angle of about 6° . The dimension of the target was about 2×5 cm² with 1 mm thickness. A Faraday cup (FC) was placed at a distance of

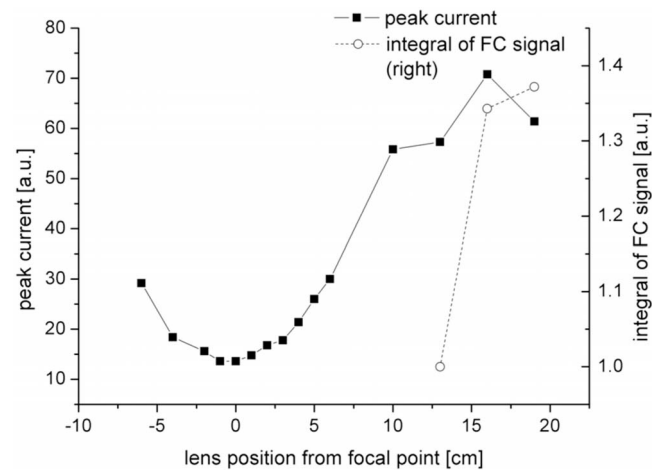


FIG. 3. (Color online) FC peak current and total FC current per pulse according to focal distance change with $f=800$ mm convex lens.

2.4 m from the target to measure the total current of plasma. The diameter and suppressor voltage of the FC were 10 mm and -2.5 kV, respectively. A cylindrical 90° electrostatic ion analyzer (EIA) was located downstream of the FC. The EIA allowed ions with a corresponding energy and charge states to the EIA applied voltage to pass through. Ion signals after EIA were enhanced and detected by a secondary electron multiplier (SEM) at a distance of 3.7 m from the target. We repeated this measurement as changing the EIA applied voltage until enough points were achieved for the charge state distribution. The obtained charge state distributions taken at SEM were scaled to the distance of FC using the relations³ that $\tau \propto L$ and $j(t) \propto L^{-3}$, where τ is the pulse length of the plasma, L is the distance from the target, and $j(t)$ is the ion current density measured at the time t . The amplitude of SEM signal was converted to the real current by comparing to the total current measured by FC. We assumed that a gain of the SEM was constant and independent to ion energy and charge states. This measurement method was the same one we used before in the experiments focused on high charge state ion production.⁴

RESULTS AND DISCUSSION

The laser power density for charge state 1+ion generation was optimized by adjusting the laser spot size on the target with a fixed laser power. A plasma total current was measured changing the position of the lens along the laser path using Al target to determine the focal point of the

TABLE I. The number of charge state 1+ions required for LIS assuming the overall efficiency of 10% after LIS extraction, the drift length to satisfy these ion yields with 1 cm² extraction areas, and plasma properties of 1 +ion at these extraction conditions for each target species.

Target	Required 1+ions for LIS (assuming 10% efficiency)	Percentage of 1+ions	Drift distance (m)	Pulse width (μ)	Peak current (mA)	Energy at peak current (eV)	Energy spread (eV)
Al	4.3×10^{11}	70	1.34	25.3	2.63	540	694
Fe	2.4×10^{11}	80	1.88	44.9	0.85	545	578
Ta	1.7×10^{11}	93	2.91	98.9	0.24	743	825

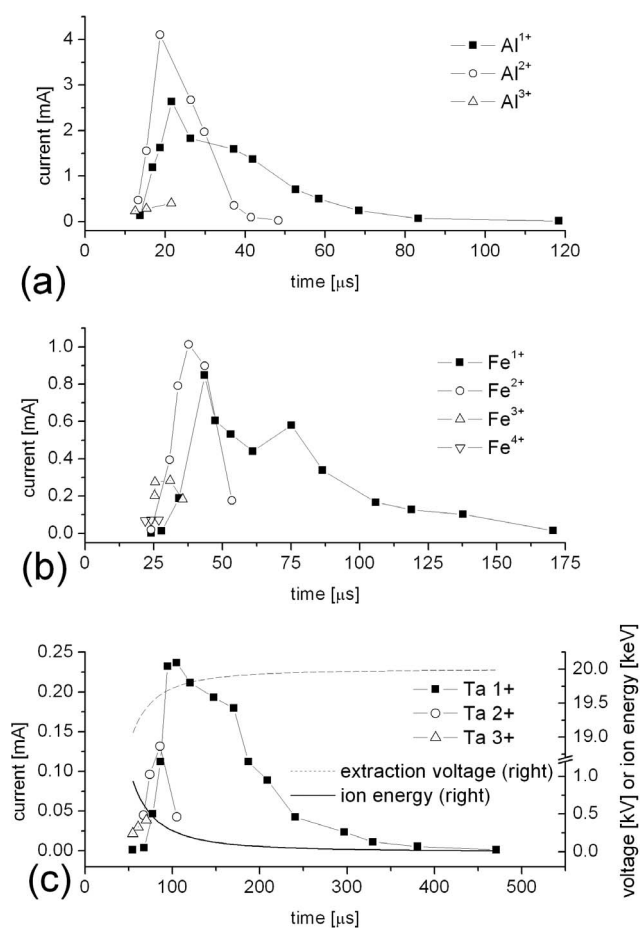


FIG. 4. Time dependences of ion current for Al (a), Fe (b), and Ta (c) with the condition listed in Table I. In (c), ion energy based on time of flight and the extraction voltage to compensate energy spread calculated by the Eq. (1) is also shown.

lens where fastest arrival ion and lowest peak current were measured. A FC peak current as a function of the distance from the focal point is shown in Fig. 3, where positive values indicate shift closer to the target. Integral value of FC signal is also shown in this figure to indicate the total ion current produced by laser shot. As shown in Fig. 3, ion yield became higher as defocusing. This is mainly because the increased target area utilized. The charge state distribution was analyzed roughly at +19 cm from the focal point where the lowest power density due to the setup limitation, therefore, the lowest charge state distribution was expected to check whether only 1+ ion was observed or not, but considerable Al²⁺ ions were recorded, so the lens position was fixed at +19 cm during experiments. The estimated spot size diameter and the laser power density were 4.3 mm and $9.1 \times 10^8 \text{ W/cm}^2$, respectively.

The charge state distributions of Al, Fe, and Ta were measured precisely with this laser power density. Based on the obtained results, the LIS performance as the external

ion source is discussed from the point of the view of the number of particles. The requirements of ¹⁹⁷Au and ²⁸Si were used to determine ¹⁸¹Ta and ²⁷Al requirements because mass number is close to each other. The minimum number of Al¹⁺, Fe¹⁺, and Ta¹⁺ ions to be injected to achieve the required ions in charge state of interest from the RHIC-EBIS without losses are 4.3×10^{10} , 2.4×10^{10} , and 1.7×10^{10} , respectively. If we assumed the overall efficiency of 10% after extraction from LIS to extraction from EBIS after charge enhancement, the necessary ion yields of Al, Fe, and Ta for LIS are 4.3×10^{11} , 2.4×10^{11} , and 1.7×10^{11} , respectively. Pulse length of over tens of microsecond is also needed to inject ions efficiently. Table I summarizes the plasma properties to satisfy these requirements. As shown in Table I, Ta had sufficient pulse length of about 100 μs and 0.24 mA peak current with required ion yield. Also, Fe had good performance with the pulse length of 45 μs. The peak current of Al was 2.63 mA, which was too high for efficient beam transport at low energies used in these studies. Note that in the case of Fe and Al, charge state distribution was not optimized for 1+ ion so the intensity of charge state 1+ ions can be higher by reducing the laser power density more. Time dependences of ion current for Al (a), Fe (b), and Ta (c) at the distance to satisfy the required ion yield are shown in Fig. 3, respectively. Although energy spread of each species was more than 100%, it can be reduced by the variable extraction voltage according to the ion energy calculated by the Eq. (1) which is shown in Fig. 4(c) with time dependence of Ta ion yield.

CONCLUSION

Plasma properties of Al, Fe, and Ta were measured to evaluate the possible use of the LIS as an external ion source for RHIC-EBIS. It was demonstrated that LIS could be optimized for 1+ ion production and required laser spot power density to produce 1+ is different for different target species. The LIS can be used as the external ion source for production of a wide range of light to heavy species considering parameters such as number of the particles and pulse length. It appears that for light materials such as Al, the LIS would benefit by a reduction in laser power density. Emittance studies and injection tests at EBIS are planned to evaluate the efficiency of the injection.

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